EXTENDED ABSTRACT

# The Influence of Horizontal Openings on the Spread of Smoke in Industrial Buildings


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***Abstract* : This article discusses the influence of horizontal openings on the smoke spread. The zone models Cfast and Branzfire are evaluated. The CFD-model FDS is used to quantify the influence. A manual calculation method is proposed based on the Heskestadt formule.**



***Keywords* : horizontal openings, separating floors, natural smoke and heat evacuation systems, zone-models, CFD**


## I. Introduction

Horizontal openings in separating floors have a major influence on the smoke spread in industrial buildings. If there is a smoke layer below the separating floor, smoke escapes through the horizontal openings. While the smoke raises in the second compartment extra entrainment of air occurs. The quantification of this entrainment is important for the dimensioning of SHEVS for the total building. Within the Belgian norm [1] and the European TR 12101-5 [2] there is no procedure to account for this extra entrainment. In this study, only natural SHEVS are considered.

## II. Formula for Plume Entrainment

There are several formula to calculate the air entrainment into a raising smoke plume [3][4]. Some, like the ideal plume formula, are based on theoretical considerations. Others are based on experimental data, like Zukoski, Heskestadt, McCaffrey or Thomas. The latter, also known as the "large fire equation", is used in the Belgian norm and in a lot of cases also in the European TR. Only if the considered smoke free height is very large, the Heskestadt equation is used in the European TR. A comparison between the entrainment formula is shown in figure 1.

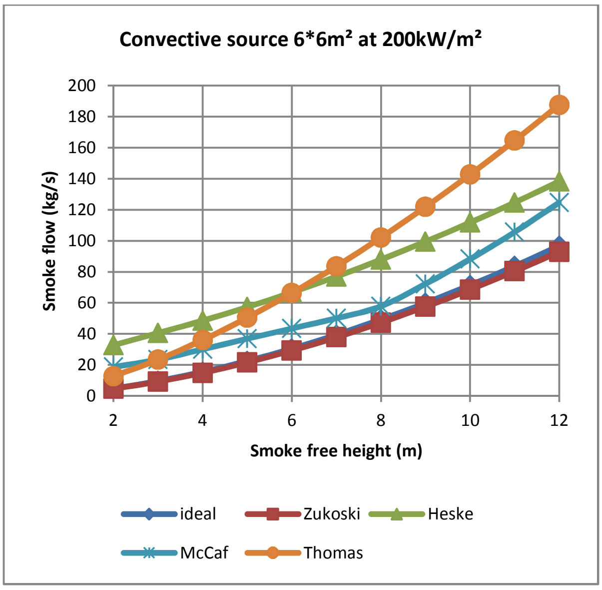


*Figure 1 : Comparison of different manual formula for plume entrainment. The heat source is 7.2MW*

Unfortunately none of the previous methods gives a solution for plume entrainment towards plumes coming through horizontal openings.

## III. Evaluation Possibilities of Zone models

The zone models Cfast [5] and Branzfire [6] are used to check their ability to simulate the air entrainment into the plumes coming through the horizontal openings. Major concerns are revealed towards the flow through horizontal openings. Especially inflow of fresh air through a horizontal opening in the ceiling in a compartment next to the compartment with the fire plume, gives unphysical results. The zone models are also unable to account for the air entrainment outside the fire compartment.

## IV. CFD : Possibilities of FDS

The CFD program FDS [7] is used to perform simulations of horizontal openings in floors. We want to compare manual formulas with the results of FDS for the second compartment (smoke free height, temperature and mass flow). Therefore it is important that horizontal roof openings are well modeled. This means that the aeraulic surface in the model is equal to the real or the calculated aeraulic surface. It is revealed that the coefficient of discharge $C_{v,fds}$ ($C_v$ which is implicitly used in FDS) in our simulations is about 0.8. It is important to notice that this value is affected by the choosen mesh and the size and geometrie of the opening. The value of 0.8 for a cubic mesh size of $(0.2m)^3$ is also revealed in recent work [8].

Figure 2 gives an impression of the obtained vector fields in the CFD simulations. The air entrainment into the plumes rising in the second compartment is shown.

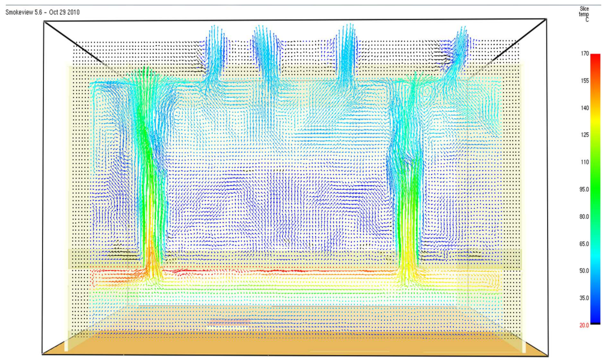

*Figure 2 :Vector field showing the entrainment of air in the second compartment (above the compartment with the fire).*

The main simulations where performed with convectieve heat of 1.8 and 7.2MW, coming through 4 or 6 openings of 1.44 or 1.96m². In the roof there where 9 openings. Table 1 gives an overview of the performed simulations.

| N° | H1(m) | H2(m) | Openings Floor(m²) | Openings Roof(m²) | conv.Power (kW) |
|---|---|---|---|---|---|
| 1 | 3.8 | 6 | (4*1.2*1.2) | (9*1.2*1.2) | 3X3X250*0.8 |
| 2 | 3.8 | 6 | (4*1.2*1.2) | (9*1.2*2.4) | 3X3X250*0.8 |
| 3 | 3.8 | 6 | (6*1.4*1.4) | (9*1.4*1.4) | 6X6X250*0.8 |
| 4 | 3.8 | 6 | (6*1.4*1.4) | (9*1.2*2.4) | 6X6X250*0.8 |
| 5 | 3.8 | 8 | (4*1.2*1.2) | (9*1.2*1.2) | 3X3X250*0.8 |
| 6 | 3.8 | 8 | (4*1.2*1.2) | (9*1.2*2.4) | 3X3X250*0.8 |
| 7 | 3.8 | 8 | (6*1.4*1.4) | (9*1.4*1.4) | 6X6X250*0.8 |
| 8 | 3.8 | 8 | (6*1.4*1.4) | (9*1.2*2.4) | 6X6X250*0.8 |
| 9 | 3.8 | 10 | (4*1.2*1.2) | (9*1.2*1.2) | 3X3X250*0.8 |
| 10 | 3.8 | 10 | (4*1.2*1.2) | (9*1.2*2.4) | 3X3X250*0.8 |
| 11 | 3.8 | 10 | (6*1.4*1.4) | (9*1.4*1.4) | 6X6X250*0.8 |
| 12 | 3.8 | 10 | (6*1.4*1.4) | (9*1.2*2.4) | 6X6X250*0.8 |
| 13 | 3.8 | 14 | (4*1.2*1.2) | (9*1.2*2.4) | 3X3X250*0.8 |
| 14 | 3.8 | 14 | (6*1.4*1.4) | (9*1.2*2.4) | 6X6X250*0.8 |
| 15 | 5.8 | 6 | (4*1.2*1.2) | (9*1.2*1.2) | 3X3X250*0.8 |
| 16 | 5.8 | 6 | (4*1.2*1.2) | (9*1.2*2.4) | 3X3X250*0.8 |
| 17 | 5.8 | 6 | (6*1.4*1.4) | (9*1.4*1.4) | 6X6X250*0.8 |
| 18 | 5.8 | 6 | (6*1.4*1.4) | (9*1.2*2.4) | 6X6X250*0.8 |
| 19 | 5.8 | 8 | (4*1.2*1.2) | (9*1.2*1.2) | 3X3X250*0.8 |
| 20 | 5.8 | 8 | (4*1.2*1.2) | (9*1.2*2.4) | 3X3X250*0.8 |
| 21 | 5.8 | 8 | (6*1.4*1.4) | (9*1.4*1.4) | 6X6X250*0.8 |
| 22 | 5.8 | 8 | (6*1.4*1.4) | (9*1.2*2.4) | 6X6X250*0.8 |

*Table 1 : configuration of the main simulations which were used for comparison with manual formula*

Several manual formula where compared with the results. Figure 3 gives an indication of the obtained results for smoke free height. The value range for the smoke free height was between 1.5 and 7m. The agreement of the Heskestadt formula, based on the equivalent circle diameter, is really good. The maximum deviation was 0.5m. Most of the deviations where within 0.2m.

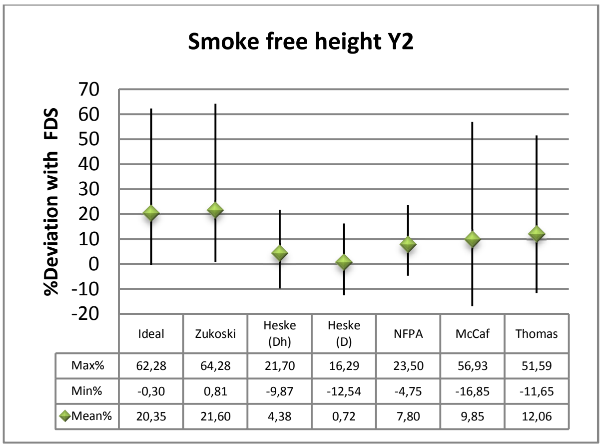


*Figure 3 : % comparison of the results obtained with manual formula for smoke free height and the results from FDS.*

## V. Manual Calculation Procedure

The results from the CFD simulations where compaired with results obtained with manual formula. The Heskestadt formula, based on the equivalent diameter and not the hydraulic diameter, gave the best fit. The procedure to calculate the entrainment through different horizontal openings can be described as follows :

*First Step*

Let $Q_j$ be the convective power coming through the horizontal opening j. This convective power can be obtained by multiplying the mass flow through opening j with the average temperature rise of the smoke layer below the intermediate floor.

$$\dot{Q}_j = M_{1j} * (T_{u1} - T_\infty)$$

As an approximation the mass flow through opening j can be calculated as the surface fraction of opening j to the total horizontal opening surface multiplied with the total mass flow coming from below the intermediate floor.

$$M_{1j} = M_1 * \frac{A_j}{A}$$

*Second step*

First the equivalent diameter of the opening is calculated :

$$D_j = \sqrt{\frac{4 * A_j}{\pi}}$$

Then we assume a certain smoke free heigt $Y_2$. The place of the virtual origin can be calculated and out of that the entrainment following the Heskestadt correlation is known :

$$z_{0j} = 0.083 * \dot{Q}_j^{2/5} - 1.02 * D_j$$

$$m_{2j} = 0.071 * \dot{Q}_j^{1/3} * \left(Y_2 - z_{0j}\right)^{5/3} + 0.00192 * \dot{Q}_j$$

The total air entrainment in the compartment is the sum of the entrainment in all the plumes :

$$M_2 = \sum m_{2j}$$

The total mass flow off smoke that has to be removed from the compartment is :

$$M_{c2} = M_2 + M_1$$

*Third step*

The temperature of the smoke layer is :

$$T_{u2} = \frac{Q_1}{M_2 + M_1} + T_\infty$$

The total mass flow that can be removed through the natural SHEVS equals :

$$M_{c2} = \rho_\infty * C_{v2} * A_{v2} * \sqrt{\frac{2 * g * (H_2 - Y_2) * (T_{u2} - T_\infty) * T_\infty}{T_{u2}^2 + \left(\frac{C_{v2} * A_{v2}}{C_{i2} * A_{i2}}\right)^2 * T_\infty * T_{u2}}}$$

*Fourth step*

An iterative procedure determines the final value of $Y_2$. Change $Y_2$ in the second and third step, until $M_{c2}$ calculated in the second step, equals $M_{c2}$ calculated in the third step.

## VI. Conclusions

Entrainment of air into smoke plumes, can be calculated with manual formula. In this thesis it is shown that the formula are also applicable in smoke raising in a compartment which is not the fire compartment. The Heskestadt formula gives good agreement with results obtained with FDS. So, manual formulas may be used and time consuming CFD can be avoided.


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